

**How Can Groups Communicate  
When They Use Different Languages?  
Translating Between Partially Shared Type Hierarchies**

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**How Can Groups Communicate  
When They Use Different Languages?  
*Translating Between Partially Shared Type Hierarchies***

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Many computer systems are based on various types of messages, forms, or other objects. When users of such systems need to communicate with people who use different object types, some kind of translation is necessary. In this paper, we explore the space of general solutions to this translation problem and propose several specific solutions to it. After first illustrating the problem in the Object Lens system, we identify two partly conflicting objectives that any translation scheme should satisfy: preservation of meaning and autonomous evolution of group languages. Then we partition the space of possible solutions to this problem in terms of the set theoretic relations between group languages and a common language. This leads to five primary solution classes and we illustrate and evaluate each one. Finally, we describe a composite scheme, called Partially Shared Views, that combines many of the best features of the other schemes. A key insight of the analysis is that partially shared type hierarchies allow "foreign" object types to be automatically translated into their nearest common "ancestor" types. The partial interoperability attained in this way makes possible flexible standards where people can benefit from whatever agreements they do have without having to agree on everything. Even though our examples deal primarily with extensions to the Object Lens system, the analysis also suggests how other kinds of systems, such as heterogeneous databases or EDI applications, might exploit specialization hierarchies of object types to simplify the translation problem.

Computer-based systems often use various types of messages, forms, and other objects to communicate information. When all the people who wish to communicate with each other use exactly the same types of objects, translation problems do not arise. However, when people want to communicate with others who use different kinds of objects, some kind of translation is necessary. The needs for such translation seem likely to become increasingly common as more and more diverse kinds of systems are linked into heterogeneous networks.

We have been particularly concerned with one instance of this problem that arises in the context of template-based office communication systems (e.g. [Malone et. al. 87b] [Tsichritzis 82]). The problem is how users of such systems can communicate with other users who have a different set of templates. Other examples of the problem arise when users of different databases exchange data or queries, or when different

companies wish to use Electronic Data Interchange (EDI) standards to exchange business forms such as purchase orders and invoices.

In this paper, we will explore the space of general solutions to this translation problem and propose several specific schemes for solving it. Our primary goal has been to design extensions to the Object Lens system [Lai et. al. 88] that allow different groups to communicate with each other when (1) the groups use some, but not all, of the same types of objects, and (2) the object types used by each group may change over time. In addition to these extensions to the Object Lens system, we have been pleased to find that our analysis has implications for other kinds of data interchange as well. In fact, the problem of sharing information among partially overlapping language communities may be regarded as one of the fundamental problems of coordination.

One of the most important general lessons of our analysis here is that several novel and attractive translation schemes are possible when the object types are arranged in an inheritance hierarchy with certain types of objects being regarded as specializations of others. In particular, unknown object types can be automatically translated into the nearest "ancestor" types they share with the receiving system. One other interesting aspect of this approach from the point of view of object-oriented system is that it translates the contents of foreign objects into object types for which the receiving system already has actions defined. In the language of object-oriented programming, this means that partial interoperability is attained by translating object *fields* without needing to translate object *methods*.

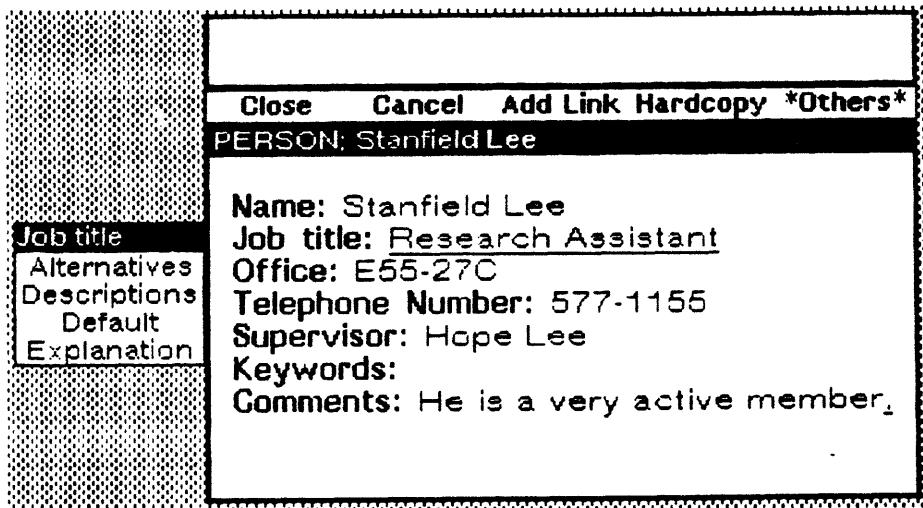
In the first section of the paper, we illustrate the problem as it arises in the context of the Object Lens system. In the second section, we state the problem more precisely in terms of the objectives that we want its solution to satisfy. In Section 3, we explore the space of possible solutions by suggesting a dimension along which to partition the space and examining a representative solution for each class. In Section 4, we propose a new scheme that combines most of the desirable features of the solutions we explored and in Section 5, we describe our implementations of the scheme in the Object Lens system. Finally, we hint at the implications that this research might have for other contexts such as heterogeneous databases and Electronic Data Interchange.

## 1. Illustration: Inter-group communication in the Object Lens system

### 1.1 Description of the Object Lens system.

Object Lens is a general tool for cooperative work and information management. It provides flexible facilities for storing and manipulating representations of many different kinds of "objects," such as messages, people, projects, and tasks. For example, it lets people specify rules to automatically filter, sort, and prioritize electronic messages they receive; and it helps people find and summarize objects in a database. The system is described in much more detail elsewhere [Lai et. al. 88].

**Figure 1.1** A template for an object type, PERSON, is displayed in an object editor.



For our purposes here, a central feature of the system is that it depends on a set of semi-structured templates for different types of objects. For instance, a person object contains fields for name, job title, telephone number, and address (Fig. 1.1), while a message object contains fields for To, From, Subject, and Date. The display-oriented object editor, shown in Fig. 1.1, uses pop-up menus to suggest alternative values for different fields, but users can put any value they desire in any field. A similar editor is used to create rules for automatically processing objects of a given type based on the contents of their fields. Users can also easily summarize the contents of collection of

objects in various formats such as tables and trees. In addition to fields and values, a template has several other properties such as a display format and a set of actions that can be applied to it. For instance, some actions are appropriate for all objects (e.g., Show or Hardcopy) while other actions are appropriate only for certain types of objects (e.g., Answer or Forward for message objects).

The set of object types currently in use by our research group at MIT is shown in Fig. 1.2. As shown in the figure, the templates for different object types are arranged in a network with some templates designated as "subtypes" (or specializations) of others. The subtypes of a given template automatically inherit from the parent template its field names, actions, and other properties. Any subtype may also, in turn, add new fields or override any of the property values inherited by the parent (Fikes and Kehler, 1985). For example, the Action Request message type has the field Action Deadline in addition to the usual fields such as To, From, and Subject. Its child, Bug Fix Request, inherits these fields and has additional fields such as Bug Name and Severity.

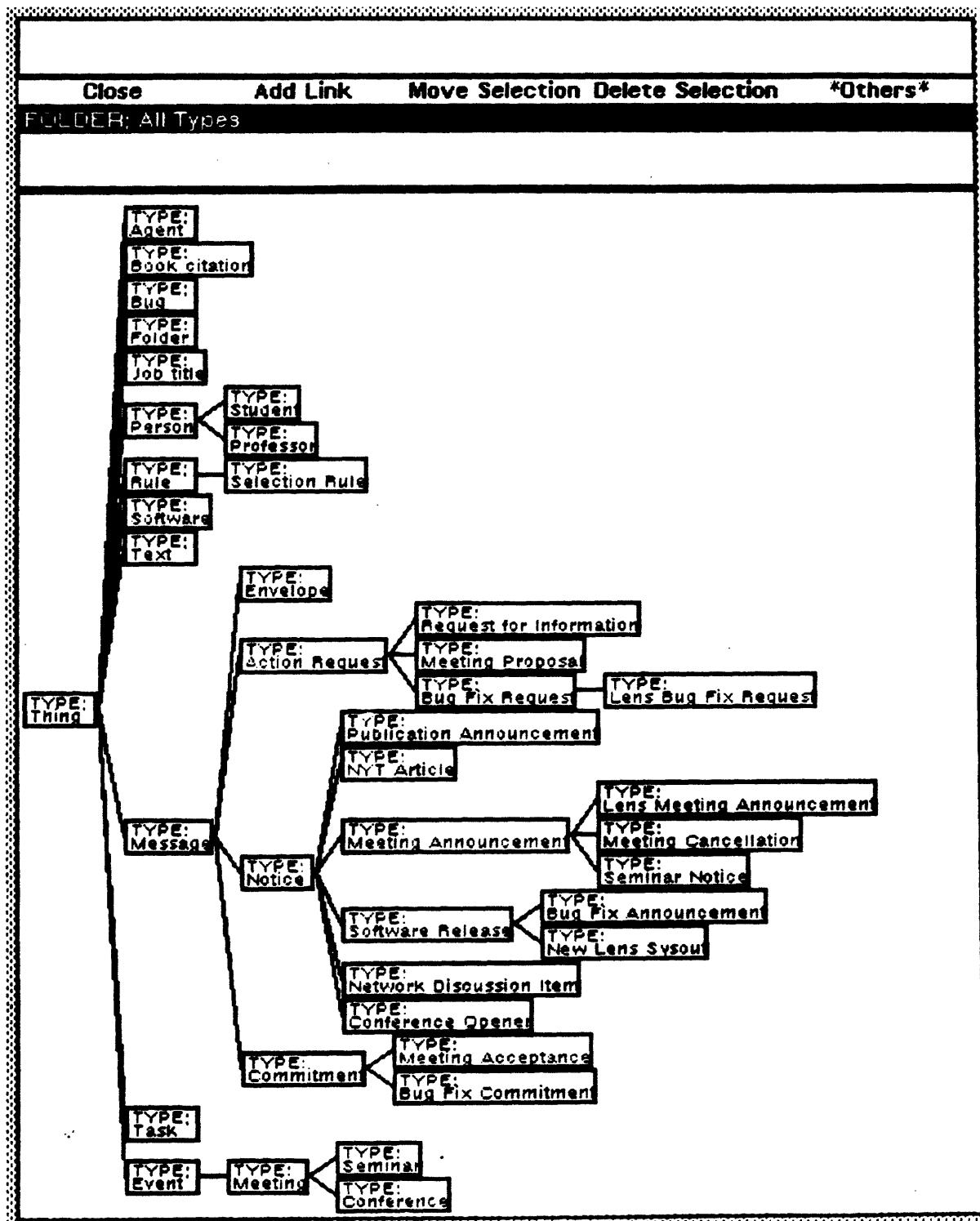
We will refer to this network of object types as a *type hierarchy* even though it need not be a strict hierarchy. The *multiple inheritance* capabilities of the underlying knowledge representation system that we use [Stefik et.al. 83] allow one message type to inherit properties from more than one parent.

## **1.2. Communicating with other groups.**

In the simplest version of Lens, all users of Lens in a local group are expected to share the same network of object types (though individual users can customize for themselves the display properties of a shared object type). The problem arises when users of an Object Lens system want to share objects with others who do not have definitions for the object types to be shared. The simplest case of this problem arises with exchanging messages, and we will illustrate the problem in this context.

Since Lens users are connected to national electronic mail networks, they often communicate with other people who do not use Lens at all, and they sometimes communicate with users of Lens at other sites that use a different set of message types.

Figure 1.2 The object type hierarchy used at MIT



One solution to this problem was the following: When a Lens message is sent--even within the local group--it is sent as an ordinary message with only the standard mail header fields in its header. All the other fields specific to this message type are sent as the first few lines of what the mail transport system regards as the body of the message. The body of the message also includes a field called "Message Type" and another one called "Text" that contains all the remainder of the message. Thus any electronic mail recipient can read a message from a Lens user. If the message is one of the specialized types with extra fields, these fields (including the field names followed by colons) will simply appear in the body of the message.

When a Lens user receives a message, the message is first checked to see whether it contains a field called Message Type and whether the name in that field is one recognized by the local group. If so, the message is treated as being of that specialized type. If not, the message is treated by Lens as the most general message type of "Message". Thus Lens users can receive messages from any connected electronic mail user. These messages are not processed by any of the special purpose rules set up for particular kinds of messages (such as Meeting Announcements or Bug Fix requests). They can, however, be processed using rules that check fields present in all messages (such as To, From, Subject, and Text). Thus the system degrades quite gracefully," taking advantage of as much of the Lens functionality as possible, even when communicating with non-Lens users.

With this scheme, Lens users can also receive and process specialized message types from Lens users at other sites--or even from non-Lens users who simply send messages with the appropriate field names typed into the body of the messages. When the sending site and the receiving site have exactly the same definitions for a given message type, this communication works as desired. A similar scheme would, of course, work for other types of objects besides messages. Instead of translating unknown object types into "Messages", however, they should be translated into the most generic type of object (called "Thing" in Object Lens). Some of our examples in the remainder of this paper will involve only messages; others will involve more general object types.

There are two kind of problems, however, that can occur with schemes like this:

- (1) If the sender and the receiver use the same name for what are actually different object types, then the incoming objects may have either extra fields, missing fields, or both. In these cases, the extra fields are inserted in the text of the message (or in the "Comments" field of an object) and the missing fields are simply treated as being empty. Even if fields with the same names are present, the sender may be using these fields in ways that are different from what the receiver expects.
- (2) If the sender and receiver use different names for what are in fact the same object types (e.g., Bug Report and Bug Fix Request), then humans can read each other's objects satisfactorily, but none of the automatic processing that could otherwise have been applied to the objects will be invoked.

No disasters occur in either of these cases, but the Lens system fails to be as helpful as it might be. The problem we will explore in the remainder of this paper is how to design systems like Lens that can retain as much functionality as possible in communication between groups without imposing excessive burdens on the different groups to coordinate their changing document type definitions.

## 2. The Problem

We formulate our problem more precisely as follows:

Let there be some number of *groups* A, B, C, etc. Each group has a set of object *types* that are shared by all members of the group. For instance, the types shared by members of group A might be denoted by  $a_1, a_2$ , etc. We refer to the set of object types used by a group as the *language* of the group. We will be particularly concerned with languages that are *type hierarchies*-- that is, languages in which some object types are specializations of others (their "parents") and automatically inherit properties from their parents.

There are also some number of *translation schemes* for translating types from one language to another. For instance,  $T_{XY}(x)$  might be a scheme that translates the types used by group X into types used by group Y. The problem is to formulate translation schemes that (1) preserve the original "meaning" of a given type of object as much as possible while (2) allowing different groups to create or change their type definitions with as much autonomy as possible. Let us explore these two objectives in more detail.

### **2.1. Preservation of Meaning**

The question of what an object, or any other expression, "means" is, of course, a complex philosophical and linguistic issue (eg. see [Putnam 75] [Jackendoff 83]). For our purposes here, we will oversimplify greatly and ignore most of these complexities. Following ([Barwise & Perry 83] [Hewitt 83]), we will not regard the "meaning" of an expression as having some (potentially falsifiable) correspondence with "reality". Instead, we will focus only on the actions that a receiver might wish to take on receiving an "expression" (eg. a document). Thus, for our purposes, two documents that evoke the same actions in the same situation, have the same "meaning". To preserve meaning of an expression, therefore, means to translate the expression in such a way that the receivers of the translated expression can perform the same range of actions they would have wished to perform had they received and "understood" the original expression. We intentionally leave undefined the term "understood" and appeal only to an intuitive sense of what it would mean for receivers to "understand" the original expression.

In the context of Lens, for example, we can interpret this criterion as follows. Take the simple scheme TAB that translates any type unknown to a group into the most general type the group has, say Message. Suppose someone in Group A sends to someone in Group B a message of type Action Request, and suppose that Group B does not have the message type Action Request. The operations that the members of the group want to apply on objects of the generic type, Message, such as Reply To, Forward, etc. are preserved under this scheme. However, the operations specific to Action Request messages such as Making a Commitment would not be available

because, for all the system knows, the object received is now an object of type Message no matter what the original group may have intended it to be.

Now suppose further that group B has a message type called Request and that another translation scheme  $T'AB$  allows translation of all objects of type Action Request to this type, Request. This translation scheme would preserve the meaning of the original type to the extent that the operations that the group has defined on Request objects overlap with the operations that the group would have defined over the set of objects that the other group classify as Action Request. If the two sets of operations are the same, then the meaning of the type is fully preserved, despite the differences in how the groups name it. If the two sets of operations do not have much in common, then the meaning of the type is not well-preserved. One can imagine situations where this definition is problematic -- e.g., receivers cannot understand the document as its senders did--but is useful enough for our purposes.

One way to ensure full semantic preservation is to require all groups to share the same set of types. However, such a requirement has its costs. The next objective captures the tradeoffs involved.

## ***2.2 Autonomous evolution of group languages***

Each group would, in general, like to be able to create or change their type definitions according to their own needs with as few constraints as possible from the other groups. We separate three aspects of this objective: maximizing expressive adequacy, minimizing the need for consensus, and minimizing the need for updates.

***2.2.1. Maximize expressive adequacy.*** Each group would like to be able to express the distinctions that are useful for its purposes. Requiring all groups to share the same set of message types makes it difficult to meet this objective of expressive adequacy because the different goals and contexts of different groups often lead them to make conflicting distinctions. For example, a manufacturing division of a company might want to make many detailed distinctions in their messages about different parts and subassemblies of many different products while the marketing division of the same

company might want to group products in a different way and make detailed distinctions about various market segments.

**2.2.2 Minimize need for consensus.** Each group would also like to be able to change its type structure while requiring as little consensus as possible from other groups. In general, type structures are not static, but evolve as needs change. The less the need for consensus from other groups, the more easily a group can change its type definitions to meet its current needs.

**2.2.3 Minimize need for updates.** When a group makes a change, other groups might need to know about the change so they can maintain consistency. For example, if one group renames a type, all the other groups that maintain a dictionary for translating types from that group would need to update their dictionaries. The cost of updates is affected by: (1) the extent to which changes need to be propagated, (2) the complexity of the data structures needed for such propagation, and (3) the extent to which the change requires modification of the existing structures. The less updates a translation scheme requires on these dimensions, the more desirable it would be on this objective.

In the next sections, we will discuss how these different objectives interact when we evaluate different translation schemes against these objectives.

### **3. The space of possible translation schemes**

There are a number of possible translation schemes that achieve, to different degrees, the objectives we discussed above. In this section, we will describe several general solutions to the translation problem, evaluate each solution with respect to the objectives discussed above, and provide specific examples of how each solution could be implemented for the Lens system.

We partition the space of possible translation schemes by using a dimension that centers around the notion of common language and its relation to group language. Even though there are other ways of categorizing possible solutions, we have found this dimension useful in placing the schemes that seem practically important. First,

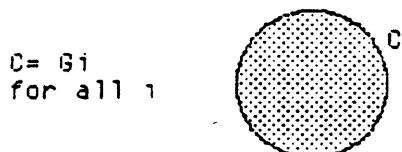
**Figure 3.1 Possible Relations between Common Language and Group Language**

$Gi$ : A Group Language  
 $C$ : A Common Language

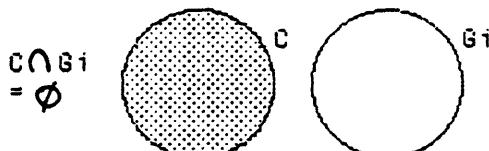
(a) No Common Language



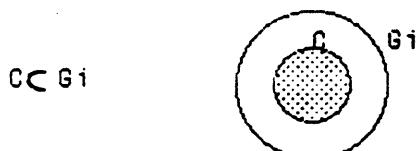
(b) Identical Group Languages



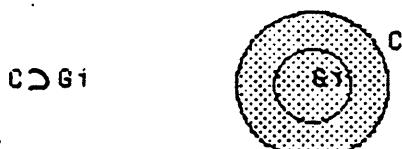
(c) External Common Language



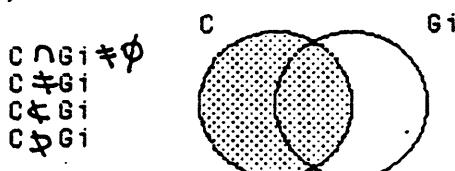
(d) Internal Common Language



(e) Superset



(f) Intersection



we define a *common language* for a set of groups as a language that all the groups in the set use to communicate with one another. In order for all groups to be able to communicate using the common language, each group must either use the common language itself or be able to translate between the common language and the group language.

Given this definition of common language, we characterize the space of possible general solutions to the translation problem in terms of the set theoretic relationships between the group languages and the common language (if any). If we consider only "pure" cases, that is cases where all the group languages have the same relationship to the common language, then, as shown in Figure 3.1, there are six possibilities. The first possibility is that (1) there is *no common language*. If there is a common language, then it may be (2) *identical* with the group languages, (3) *non-overlapping* with the group languages, (4) a *subset* of the group languages, (5) a *superset* of the group languages, or (6) *partially overlapping* with the group languages.

The first four of these possibilities represent interesting practical solutions to our general problem, and we will describe them in the remainder of this section, using the terms (1) *no common language*, (2) *identical group languages*, (3) *external common language*, and (4) *internal common language*. The fifth and sixth possibilities and "hybrid" cases where some group languages have one relationship to the common language and other groups have another relationship can all be analyzed in terms of the first four "pure" possibilities. We discuss these special cases briefly at the end of the section along with several other possibilities.

### **3.1 No Common Language**

In a scheme of this type, there is no common language that is shared by groups that wish to communicate. Instead, each pair of groups must be able to have pairwise translations made into and out of each other's languages. This is, in a sense, the situation that actually prevails in the real world of natural languages such as English, French, and Japanese. In the world of computer-based documents, this scheme implies that there are translating programs for each pair of groups. The most general form of such programs would involve "dictionaries" that provide translation rules for each

type from a source language into some type in the target language. Type and map derivations in the Federated Architecture for information sharing [Heimbigner & McLeod 1985] illustrates an example of such a dictionary in the context of database integration.

In Object Lens, this solution could be implemented by letting each group have a dictionary for each other group with which it communicates. Whenever an object is received from one of these groups, Lens would use the dictionary to translate the incoming object into a type understood by the receiving group. This translation could involve much more than just changing the type name. It might, for example, include moving and transforming values within the fields of the object. For instance, the following rule might be contained in a dictionary for objects that group B receives from Group A:

IF the object type is GRAUDATE STUDENT  
and the value of SUPPORT field is TA,  
THEN convert the object type to INSTRUCTOR,  
and map the fields as follows:  
Student ID -> SSN  
TranslateDPT(DEPARTMENT) -> DPT

The rule says that if the received object is of type GRAUDATE STUDENT and if he is teaching a course, then it should be translated into an object of type INSTRUCTOR after renaming the field 'STUDENT ID' to 'SSN' and 'DEPARTMENT' to DPT'. Furthermore, the function TranslateDPT will be applied to the value of DEPARTMENT in the original message to obtain a value that is understood by Group B (e.g. "Computer Science" to "CS").

*Evaluation.* This scheme is very flexible in the sense that it can provide case-specific translations in fine-grained details. In this way, the scheme can fully preserve meaning provided that the following condition is met:

*If there is a one-to-many mapping from a Group A's type,  $X$ , to Group B's types,  $Y_i$ , then there should be other characteristics of documents of type  $X$  that allow unambiguous selection of the  $Y_i$  to which  $X$  should be mapped.*

In the above example, the rule that translates Group A's GRADUATE STUDENT type to Group B's INSTRUCTOR is only a partial map because only some of the objects of GRADUATE STUDENT type are mapped to the type in B. To be able to translate all the GRAUDATE STUDENT objects properly, there has to be more than one type in B to which GRADUATE STUDENT is mapped. Hence, there have to be some characteristics in objects that allow the translation scheme to determine which types in B the objects should be translated. In the example, the value TA in the SUPPORT field served as one such characteristic.

This scheme also satisfies some of the objectives of autonomous evolution fairly well. Since the group is not constrained to have any part of its hierarchy shared with other groups, expressive adequacy is not limited. Since setting up translation rules within a group does not affect any other group, no consensus is required. However, a problem with this scheme is that it could be quite costly to set up and maintain. When a group changes its type structure, the change will, in general, have to be propogated to all other groups with which this group communicates so that the other groups can change their translation rules or dictionaries. Each group needs a dictionary for all the other groups with which it communicates. If there are  $n$  groups communicating with one another, there would, in general, need to be  $n(n-1)$  dictionaries. Also, whenever a new group joins, all the other groups would have to set up a dictionary for that group, and the new group would have to set up dictionaries for all the existing groups.

*Applicability.* This scheme would be appropriate when the groups already use their own languages and when the efforts to build translation rules and dictionaries for the other groups are justified. Such efforts may be justified, for example, if the number of groups that need to communicate is small or if the groups themselves are stable and their type hierarchies do not change often.

### ***3.2 Identical Group Languages***

In this scheme, the common language is the same as any group language. That is, all groups are required to use the same language and communicate through that language. Examples of this scheme include the adoption of global standards such as Dewey Decimal Classification System among libraries or Computing Reviews Classification Scheme used for categorizing literature in computer science. In the context of Object Lens, adopting this scheme means that all the groups share the same object type hierarchy.

*Evaluation.* In this scheme, meaning is fully preserved because the types and the operations defined on them are the same for all the groups. However, expressive adequacy is quite limited and the need for consensus is quite large. Since all groups have to agree on changes, the only changes that are easy for a group to make will be those that do not affect other groups or those that are valuable to all groups. Even these changes may require a significant overhead to come to agreement. This scheme also requires that all changes be propagated to all groups. However, whereas each group has to deal with the consequences of these changes in the No Common Language scheme, this scheme allows the consequence management to be 'centralized' in that whatever consequences there are can be well thought out once and distributed to each group. For example, one can distribute a translation routine from the old type to the new type together with a type change notice.

*Applicability.* This scheme would be useful when there are not already well-established groups and when the groups do not differ greatly in their needs. This may occur, for instance, when the domain is very restricted or artificial, or because there is a well-accepted theory about the domain, or simply because the groups share the same goals and environments insofar as they need to communicate. For example, there may be a small set of generic message types such as Request and Commitment that are useful in almost all office environments [Winograd & Flores 86].

### ***3.3 External Common Language***

In this scheme, each group uses its own separate language for communication within the group, but there is a single common language for communication between groups. A group communicates with another by first translating its language into the common language, and then having the receiving group translate the common language into its own group language. In this way, each group only needs to know its own language and how to translate it into and out of the common language. An example would be the adoption of an international language such as Esperanto. Another example can be found in the idea of abstract data type that allows data structures to be implemented in any locally convenient ways as long as they maintain a consistent interface to the outsiders ([Liskov & Zilles 74] [Guttag 77]).

If Lens were to use this scheme, there would be a common type hierarchy shared by all groups in the sense that each group would know how to translate its own types into the types in this hierarchy and vice versa. For example, suppose that Group A wants to send an object of type, Teaching Assistant, to Group B which does not have that type, but has a type called Instructor. Suppose that the common hierarchy has an object type called Student with an attribute called Support. With appropriate rules set up between the common object and the group objects involved, the Teaching Assistant object can be first translated into an instance of Student with the Support attribute set to TA, which would then be translated to an Instructor object in Group B.

The translation can be done in the same way as described above for the No Common Language scheme--that is, by means of a dictionary containing translation rules. The differences between this scheme and No Common Language scheme is that in this scheme all the groups need to know only how to translate back and forth between their own languages and the common language. So each group only needs two dictionaries, one for translating to and the other for translating from the common language; overall only  $2n$  dictionaries are needed for  $n$  groups.

*Evaluation.* This scheme can fully preserve meaning provided that the condition discussed in Section 3.1 is met for translations both into and out of the common language-- that is, when there are one-to-many mappings between types, there must be some other characteristics of the documents that enable the unambiguous selection of a target type. However, often this condition is not satisfied. Hence, in general, the

more translations a scheme requires, the less it is able to preserve meaning. Since an External Common Language scheme requires more extra translation steps than the others we have considered, we expect that it is less likely to preserve meaning than the others.

Since each group can design its own language without being constrained by others, the group languages can presumably have as much expressive adequacy as desired. The need for consensus applies only to deciding what the common language should be and how it should be modified. Any change in a group language need not be propagated to other groups; only the mapping between the changed type and the relevant types in the common language need to be changed. If a type in the common language changes, all the groups that have a local type mapped to that type need to know about the change. But, even in this case, it is only the mappings, not the group languages themselves, that have to be changed.

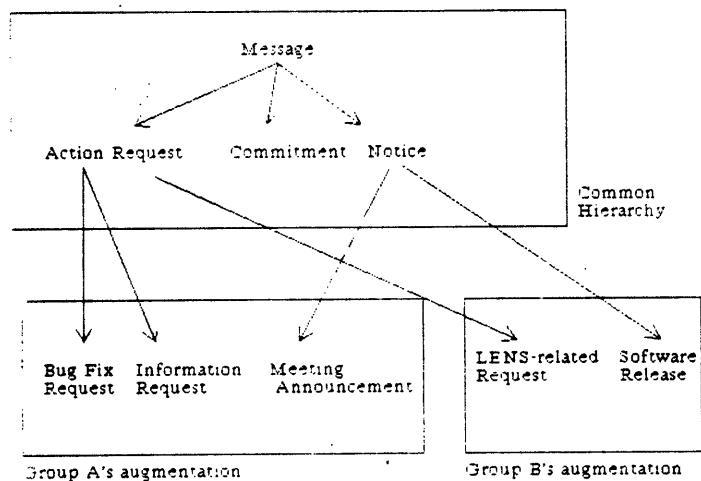
*Applicability.* This scheme would be useful when groups that already use different languages want to communicate and when the cost of setting up translation rules or dictionaries for all the groups is too high. Presumably it is for these reasons that people propose an international language or use English as one. Also, this scheme might be useful when there is a language that is expressive enough, but difficult to use for that reason. For example, we can define a language to be the union of all group languages for the cases where such a union is meaningful. Such a language could express all the distinctions that are of interest to any group, but it might be difficult to use if the types are too fine-grained or place too much cognitive load on the user. Such a language, although not suitable as a group language, might serve as the common language.

### **3.4 Internal Common Language**

For schemes in this class, every group has a part of its language that is shared with all the other groups, and the groups use this shared language to communicate with one another. For example, different academic specialists (say, physicists and anthropologists) may each have their own technical vocabularies, but they can usually communicate with specialists from different fields using ordinary English.

A particularly interesting example of this class arises when the languages are type hierarchies. If all the groups share the root node and other types in the top part of the type hierarchy (i.e., they share the most general types), then all the other types that exist in the separate group languages are specializations of types in the common language. This makes it especially easy to translate group types into the common language, as we illustrate below.

**Figure 3.2 A Common Hierarchy and its Local Augmentations**



We have explored a scheme of this type for Lens called the Local Augmentation scheme. For instance, all groups might share the message types that are useful almost everywhere, such as `Message`, `Action Request`, `Commitment`, and `Notice`. Then each group is allowed to locally augment the hierarchy by creating subtypes of these shared types (See Fig. 3.2). When group A sends to group B a message of type, say, `Meeting Announcement`, the type is automatically translated into the nearest ancestor in the common hierarchy, in this case `Notice`. Those fields of the type `Meeting Announcement` (such as `Topic`) that are also in the nearest common ancestor, `Notice`, are preserved as they are; those that are not in the ancestor (such as `Meeting Time` and `Meeting Place`) are treated as a part of the main text and put in the beginning of the `Text` field. Of course, if group A sends a message of a type that is already in the common hierarchy, then no translation is necessary.

One way of implementing this scheme is to have each object include the information about its type in the object type hierarchy used by the sending group. If this type is not in the common hierarchy shared by all groups, the object also contains: a) the name of the sending group and b) the nearest "ancestor" of the object type in the common hierarchy. This way, receivers in the sending group can process the message as being of exactly the type intended by the sender, and receivers in all other groups can process it as being of the nearest "ancestor" type in the common language.

*Evaluation.* This scheme preserves meaning to the extent that the type structure is shared. If the message is of a type in the common hierarchy, then its meaning is fully preserved. If not, then its meaning will be abstracted away to the degree that its ancestor in the common hierarchy preserves its properties. This scheme allows a great latitude in expressive adequacy since each group can add as many types as desired to express distinctions that are important to them. The only constraint on expressive adequacy is that groups cannot completely ignore distinctions made in the common hierarchy. For example, suppose, as before, that the common hierarchy classifies Message objects into the speech act categories such as Action Request, Notice, and Commitment. If a group does not want to use this speech-act based categorization, it can add other children of Message and use them for internal communication, but the group members will still receive messages from other groups based on the speech act categorization.

This scheme only requires consensus among groups on what the common hierarchy should be, and it only requires the propagation of changes in this common hierarchy. The changes made locally within a group need not be propagated to other groups. However, a change in the common hierarchy needs to be propagated to all groups. Furthermore, unlike in the External Common Language scheme, such a change might require much change in the local structure. For example, all the groups that have rules or subtypes of the modified type might have to make necessary adjustments.

- *Applicability.* This scheme would be useful when (1) there do not already exist numerous well-established and incompatible language groups, (2) there are important commonalities across groups, and (3) there are also significant local variations among

groups. For instance, it seems quite useful in the Lens environment to have a set of common message types used by all groups (such as Action Request, Commitment, and Meeting Announcement), and to also let each group develop their own specialized message types for their own unique situations. The X.400 standards for electronic messaging are compatible with this approach since they include a field for specifying a message type, and leave open the possibility of different groups developing their own conventions about how this field is used.

### ***3.5 Common Language as a Superset of Group Languages***

In this scheme, the common language is a superset of the group languages. An interesting instance of this scheme is the following: Suppose that different groups maintain different type hierarchies. However, when a group receives an object of unknown type, that type and any of its supertypes that are not known locally are automatically imported into the local type hierarchy. In this case, the common language is the union of all the groups' type hierarchies, because any object in the union can be used to communicate among the groups.

*Evaluation.* In this scheme, meaning can be fully preserved if the types are imported together with all their operations. However, doing so can be costly; or if the operations are written in a programming language not supported in the receiving group, automatic importation can be impossible. This scheme allows the groups to express whatever they want without much need for consensus. However, this scheme does not address the problem of how the imported objects are related to the local types. It also has the potential problem of creating different types with the same name, thus "cluttering" the type space. Also, in this scheme, the update propagation can be costly if we want to maintain consistency between the imported type and the original. Any change made to a type would have to be either broadcast or sent to all the groups who imported the type. The latter requires that whenever a group imports a type, the originating group would have to be notified.

*Applicability.* In spite of the potential costs of this scheme, it is simple and offers a large degree of autonomy for groups. It can be practically useful when the costs of importing foreign objects is not too high. For example, if only a small number of

people are involved, updates may be rare (and their total cost low) and there may be little danger of cluttering the type space. The usefulness of this scheme is also increased when the object types are hierarchically arranged and some types are known to both groups. In this case, a form of the local augmentation scheme can be used to apply operations from a shared supertypes to newly imported types.

### **3.6 Other translation schemes**

We have discussed above five of the six set-theoretic possibilities (Fig. 3.1) for the relationship between the common language and a group language. We can also have (a) hybrid cases, where some groups have one relationship with the common language and other groups have different relationships, and (b) sequential composition of the basic cases. We show elsewhere [Lee & Malone 88b] that these other possibilities, as well as the sixth possibility not discussed (Intersection in Fig. 3.1), can all be analyzed as combinations of the five schemes discussed above. In [Lee & Malone 88b], we also discuss a translation scheme that exploits the subsumption property of certain type hierarchies. In this scheme, a message is automatically classified into the type hierarchy according to what fields it contains [Schmolze & Lipkis 83]. This scheme requires no explicit agreement about the types used, but it does require agreements about the field names themselves as well as some other restrictions on the form of the type hierarchy.

### **3.6 Summary of translation schemes**

Table 3.1 summarizes the different classes of translation schemes we have considered. The detailed discussions above are summarized in the table by rough qualitative rankings of the schemes on each objective. In each column, the schemes that in general satisfy the objective better receive more stars. For example, the schemes that receive *more* stars in the column, Need for Consensus, have *less* need for consensus.

As we have seen, there is a complex tradeoff between the objectives we are trying to achieve. For example, the pairwise translation scheme used when there is no common language allows full expressive adequacy and little need for consensus, but at the cost of more need for propagation of changes. An identical group languages scheme has full

preservation of meaning, but much less expressive power. And any scheme that uses trivial translation rules (e.g., all foreign message types are translated into generic Messages) can reduce the need for consensus and for propagation of change at the expense of preservation-of meaning.

**Table 3.1 Evaluation of the different classes of translation schemes.**

	Meaning Preservation	Expressive Adequacy	Need for Consensus	Need for Updates
No Common Language	**	*****	*****	*
Identical Group Languages	*****	*	*	***
External Common Language	*	***	***	****
Internal Common Language	***	**	**	**
Superset	***	****	****	*

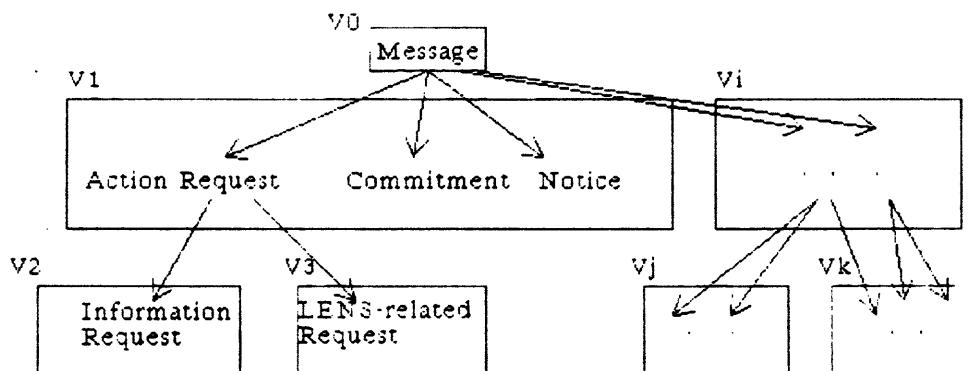
We have shown how the classes of translation schemes we have discussed exhaustively partition the space of possible solutions. However, the examples of these schemes that we considered are by no means the only possible ones. For instance, there may be other schemes that exploit special properties of particular languages just as the Local Augmentation Scheme exploits the inheritance property of type hierarchies.

#### 4. An Attractive Composite Scheme: Partially Shared Views

In this section, we present a composite scheme, called Partially Shared Views (PSV), that combines some of the best features of the basic schemes discussed above: It allows groups to share some object types, to set up translation rules for other object types, and to use default translations into shared "parent" types for still others.

This scheme exploits the notion of views to modularize related type definitions and make relations among such modules explicit ([Barber 82] [Goldstein & Bobrow 81]). A view is a set of object types and their relations. A view  $V_2$  is a subtype of  $V_1$  if some of the message types in  $V_2$  are specializations of ("children" of) the message types in  $V_1$ . Figure 4.1 shows a few examples of views.

Figure 4.1 Examples of Views



#### 4.1 How It Works

When a group  $G$  receives an object from another group, then one of the following happens:

- (1) *If the object belongs to a view that has been 'adopted' by the group, then the object is treated as being of its original type.*

(2) If the object is from a view that has not been adopted by the group, then:

- (a) if the object meets a pre-specified criterion (e.g. if it is from the system administrator), then the view that it belongs to is automatically adopted and the object is treated as in (1).
- (b) if the group has a translation rule set up for the object's type, then the object is translated according to the rule.
- (c) if the group has a translation rule set up for a supertype of the object (but not for the object type itself), the object is treated as the supertype and translated accordingly. That is, all the fields that belong to the supertype get translated as specified in the translation rule, and all the fields that are not included in the supertype are simply added to the beginning of the comment field of the object.
- (d) Otherwise (if none of the above conditions holds), the object is automatically translated into the most specific supertype in the most specific view that is shared by the sending group and the receiving group. When the translated object is shown, the information about its original type and view is preserved so that the receiving group can, if it wishes, set up translation rules for this new type or, possibly, adopt the entire view to which it belongs.

The above algorithm is based on the following assumptions:

1. All groups share the default view, V0, which consists of the most general type (e.g. Thing).
2. When a group adopts a view, it also adopts all the views which are its ancestors.
3. Each object includes the following information:
  - a. the type of the object, t.
  - b. a globally unique name of the view within which this type is defined, v.
  - c. the "genealogy" of the object, such as  $\{(t_1, v_1), \dots, (t_n, v_n)\}$ , where the  $v_i$ 's are the names of ancestor views of v ordered from most specific to more general, and each  $t_i$  is the most specific ancestor type of t within  $v_i$ .

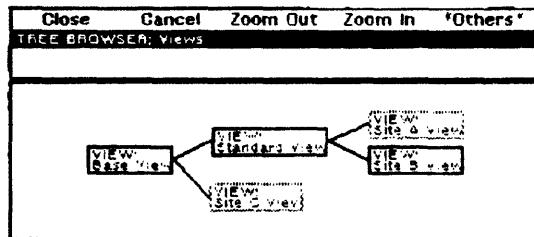
The actual algorithm used is actually a bit more complex than presented here because multiple parents are possible. In these cases, the genealogy information has to be presented as a nested list and we have to make sure that we deal with multiple parents appropriately. But, for simplicity, we assume below that each object has only a single parent.

## 4.2 Illustration

We illustrate the PSV scheme by describing its implementation in the Object Lens system [Lai et. al. 88]. Object Lens and PSV are implemented in Interlisp-D (and Loops) on Xerox 1100 series workstations connected by an Ethernet. All the features described below have been implemented and have received limited testing at our site.

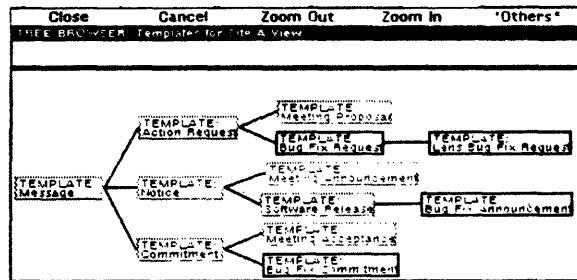
The following scenario illustrates how PSV works. This hypothetical scenario is inspired by our experience with test sites for the Information Lens, and illustrates the use of PSV for translating messages only. (Other kinds of objects are not included in this scenario). Site A is loosely based on our own group at MIT and Site B is loosely based on our primary external test site. Suppose there are five views related as shown in Figure 4.1. The Base View is the parent of all the other views; it contains only the most general message type: Message. The Standard View is intended to contain a set of templates that would be useful for almost any group using Lens. Here, we illustrate one possible such set by three message types based on speech acts (Action Requests, Notices, and Commitments) and several specializations of these speech acts such as Meeting Proposals and Meeting Announcements. Site A's view adds to the Standard View several specialized message types that are of use in that particular group (e.g., Bug Fix Requests and Bug Fix Announcements). Figure 4.2a shows all the templates used by Site A. The templates that belong to the Site A View itself are shown in blackshade, and the templates belonging to the Base View and the Standard View, are shown in grayshade. Site B's view, as shown in Figure 4.2b, is a different specialization of the Standard View. Site C's view, even though not shown here in detail, is included to demonstrate that no site is required to adopt the Standard View. For instance, Site C might use some basis for message type categorization that is different from the speech act scheme.

**Figure 4.1 A sample set of views..**

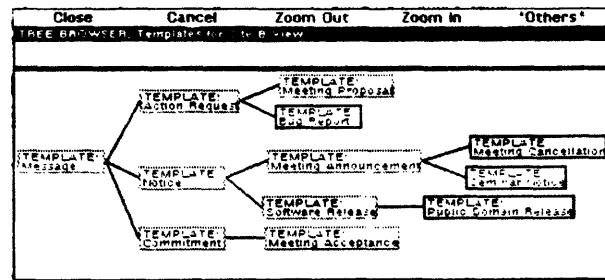


**Figure 4.2 Templates in the views adopted by Sites A and B, respectively.**

**(a) Site A**



**(b) Site B**



#### *4.2.1 Explicit translation rules*

Suppose that someone at Site B sends the message of type Bug Report shown in Figure 4.3a to Site A. We further assume that Site A has the following translation rule set up for this type:

**IF the message is of type Bug Report in Site B View  
and the value of the field System is Lens,  
THEN change its type to Bug Fix Request in Site A View  
and use the value of Bug Name for Bug  
and the value of Impact for Severity.**

**Figure 4.3** A Sample message and its translation into the views used at two other sites.

**(a) The original message**

Close	Cancel	Send	Add Link	"Others"
BUG REPORT: Lens bug				
<p><b>Subject:</b> Lens bug</p> <p><b>To:</b> BugFixers@SITE-A</p> <p><b>From:</b> Jin Lee</p> <p><b>cc:</b> Lens-Users@SITE-D</p> <p><b>Reply-to:</b> mike@SITE-B</p> <p><b>Action Deadline:</b> this week</p> <p><b>System:</b> Objet Lens</p> <p><b>Lisp System Date:</b> 1-Mar-88 02:24:13</p> <p><b>Bug Name:</b> Heart Breaking Bug</p> <p><b>Impact:</b> Moderate</p> <p><b>Machine:</b> DTiger</p> <p><b>Frequency:</b> often</p> <p><b>Keywords:</b> editor bug</p> <p><b>Text:</b> When you open the translation editor, a strange character looking like a heart appears, followed by a break.</p> <p>-Mike</p>				

**(b) Translation to Site A's view  
based on an explicit translation  
rule**

Close	Cancel	Send	Add Link	"Others"
BUG REQUEST: Lens bug				
<p><b>Subject:</b> Lens bug</p> <p><b>Date:</b> 2-Sep-89 16:21:31</p> <p><b>To:</b> BugFixers</p> <p><b>From:</b> Jin Lee</p> <p><b>cc:</b></p> <p><b>Reply-to:</b> Mike@SITE-B</p> <p><b>Action Deadline:</b> this week</p> <p><b>Bug:</b> Heart Breaking Bug</p> <p><b>Severity:</b> Moderate</p> <p><b>Software System:</b></p> <p><b>Keywords:</b> editor bug</p> <p><b>Text:</b></p> <p>Message Type: Bug Report</p> <p>System: Objet Lens</p> <p>Lisp System Date: 1-Mar-88 02:24:13</p> <p>Machine: DTiger</p> <p>Frequency: often</p> <p>When you open the translation editor, a strange character looking like a heart appears, followed by a break.</p> <p>-Mike</p>				

**(c) Default translation for Site  
D into the nearest shared  
"ancestor" type**

Close	Cancel	Send	Add Link	"Others"
BUG REQUEST: Lens bug				
<p><b>Subject:</b> Lens bug</p> <p><b>Date:</b> 2-Sep-89 16:36:57</p> <p><b>To:</b> Lens-Users@SITE-D</p> <p><b>From:</b> Jin Lee</p> <p><b>cc:</b></p> <p><b>Reply-to:</b> Mike@SITE-B</p> <p><b>Action Deadline:</b> this week</p> <p><b>Keywords:</b></p> <p><b>Text:</b></p> <p>Message Type: Bug Report</p> <p>Bug Name: Heart Breaking Bug</p> <p>Impact: Moderate</p> <p>System: Objet Lens</p> <p>Lisp System Date: 1-Mar-88 02:24:13</p> <p>Machine: DTiger</p> <p>Frequency: often</p> <p>When you open the translation editor, a strange character looking like a heart appears, followed by a break.</p> <p>-Mike</p>				

This rule causes the Bug Report shown in Figure 4.3a to be translated into the Bug Fix Request shown in Figure 4.3b. Furthermore, all the operations applicable to the translated type are applied to the message. For example, if the receiver at Site A has set up a rule to automatically archive all Bug Fix Requests into a database, then this message will be so archived.

#### *4.2.2 Default Translation*

Now suppose that the original message in Figure 4.3a is also received by a Lens user at Site D, and suppose further that Site D has adopted only the Standard View with no local augmentation of its own and no explicit translation rules. Figure 4.3c shows how the original message would be automatically translated by default into the nearest shared "ancestor" type used by both Sites B and D. In this case, the nearest shared ancestor type is Action Request, so the message is translated into an Action Request and the contents of the Action Request fields (including Action Deadline) are carried over into the new message. All the other fields from the original message are simply inserted in the text field of the new message. When users at Site D receive this message, any rules they have set up for Action Requests will be applied to it.

#### *4.2.3 Maintaining views and translation rules*

We expect that, in most cases, the adopting of views and the creation of translation rules will be done by the same "system administrators" who maintain each local group's message types. In these cases, most users would just load new versions of their system when announced by their local system administrator and they would not even need to be aware of what or how views were being used. Some users, however, might have communication needs that differ significantly from others in their local group. For instance, they might communicate frequently with people at another site who use a number of specialized message types for which the local system administrator has not created any specialized translation rules. In these cases, the individual users might want to adopt another view or create their own translation rules, and the PSV scheme allows them to do this quite easily.

#### *4.2.4 Implementation issues*

In our prototype implementation of this scheme, we did not attempt to deal with all the issues that would arise in implementing it on a large scale. In this section, we briefly sketch a few of these issues and possible solutions:

(1) *User interface for translation rules.* In our prototype implementation, the user interface for specifying translation rules was relatively primitive. There are a variety of attractive possibilities for a more graceful interface, however. In the Object Lens environment, for example, it would be consistent to have translation rules defined as specializations of the generic rules used by all agents. These rules could specify in their IF conditions, the criteria for messages to be automatically translated, and their THEN actions could contain a set of "mapping" objects, each one specifying a source field (from the original message), a destination field (in the translated message), and an optional conversion function to be applied to the field contents. An alternative approach for specifying translation rules would be to let the user "draw" connections between the fields of the source object type and the destination object type using "rubber banding" lines. This approach was used, for example, in the KEEconnection system for importing information from remote databases into knowledge-based systems [IntelliCorp 87].

(2) *Storing and transmitting view definitions.* In a large scale implementation of a scheme like this, a critical issue is where and how views (i.e. sets of object type definitions) would be stored and transmitted. We believe it would be desirable to have two options: (a) Users who have convenient access to shared file servers would presumably like to be able to store and retrieve views using these file servers. (b) Users who do not share access to file servers should also be able to simply mail view definitions to each other.

(3) *Including type names and "genealogy" in objects.* We believe it is desirable to have objects be "self-contained" in the sense that any receiver can tell, by looking at the object alone, how to interpret it (i.e., whether this is a view and type already known to the receiver). It is also desirable, especially in the case of message objects, for the objects to be readable by human receivers who are not users of the PSV scheme. These two objectives present a slight conflict since including globally unique identifiers for

types, views, and type genealogies will require including some "ugly" identifying information in the human readable objects. We believe, however, that in most cases a satisfactory solution will be to compactly encode this information in a character string that is "hidden" somewhere in the object. For example, with messages, this string can be either (a) placed in a Message Type field in the message header (analogous to the Message Identifiers used by many current mail systems), or (b) "buried" at the very end of the message after a human readable label like "Identifying information:".

#### **4.3 Evaluation**

PSV is a composite of several of the basic schemes discussed in Section 2. As noted above, between groups that share the same view, the scheme is an instance of the Identical Group Language scheme. To the extent that the groups have translation rules between views, it serves as an instance of the No Common Language scheme. To the extent that one automatically adopts views, it is an instance of the Superset Common Language scheme. PSV, however, provides a finer control over automatic adoption by allowing users to specify the conditions under which a view should be automatically adopted. When the groups share only some views and do not yet have translation rules set up between the views not shared, the scheme acts as an instance of the Internal Common Language scheme. The scheme thereby allows finer-grained adoption of translation methods among different groups while still providing a unifying framework. Within this framework, a group can weigh the importance of different objectives in different cases and select a translation method appropriate for each case. For example, if it is quite important for a group to understand another group's language, then it can decide to share the same view or adopt a view where translation rules can be set up precisely. On the other hand, if such precise understanding is not important enough to justify the effort, the group can create its own view and rely on the default translation of the type into its nearest ancestor in the shared view.

#### **4.4 Applicability**

Since the Partially Shared Views scheme combines many of the best features of the other schemes it is potentially relevant in very many situations. In a sense, each of

the other schemes is a special case of this one. This scheme, therefore, may require somewhat greater implementation complexity, but it allows a great flexibility in using a combination of different translation schemes for different situations.

For instance, this approach seems clearly desirable for the Lens system. For similar reasons, the approach also seems desirable for many other office systems. We describe below, in Section 6, how the Local Augmentation scheme could let systems using different subsets of EDI (Electronic Data Interchange) forms achieve a certain degree of interoperability by agreeing on generic global standards that leave room for augmentation by different subgroups. The Partially Shared Views scheme seems even more appropriate in these situations because it allows many overlapping subgroups to use their own standards for communication with members of the same subgroups, and also to set up translation rules for communication with other subgroups, even when there are no significant global standards.

## **5. Other Applications**

In this section, we illustrate the generality of our scheme by applying it to two other problems that require exchanging information between groups that use different types of data: (1) the problem of integrating heterogeneous databases, and (2) the problem of exchanging electronic business forms between organizations (Electronic Data Interchange, or EDI).

### **5.1 Database Integration**

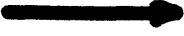
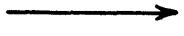
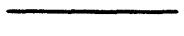
It is becoming increasingly common in organizations today for people to want to retrieve related information from a variety of different databases, all of which are stored and maintained separately, and all of which have different data formats ([ElMasri et. al. 86] [Batini et. al. 86]). For example, a bank might want to prepare a single consolidated statement of all their dealings with a given customer, even though the customer had many different types of accounts with the bank (e.g. checking, saving, loans), each of which was stored by different parts of the bank in different formats in different computers.

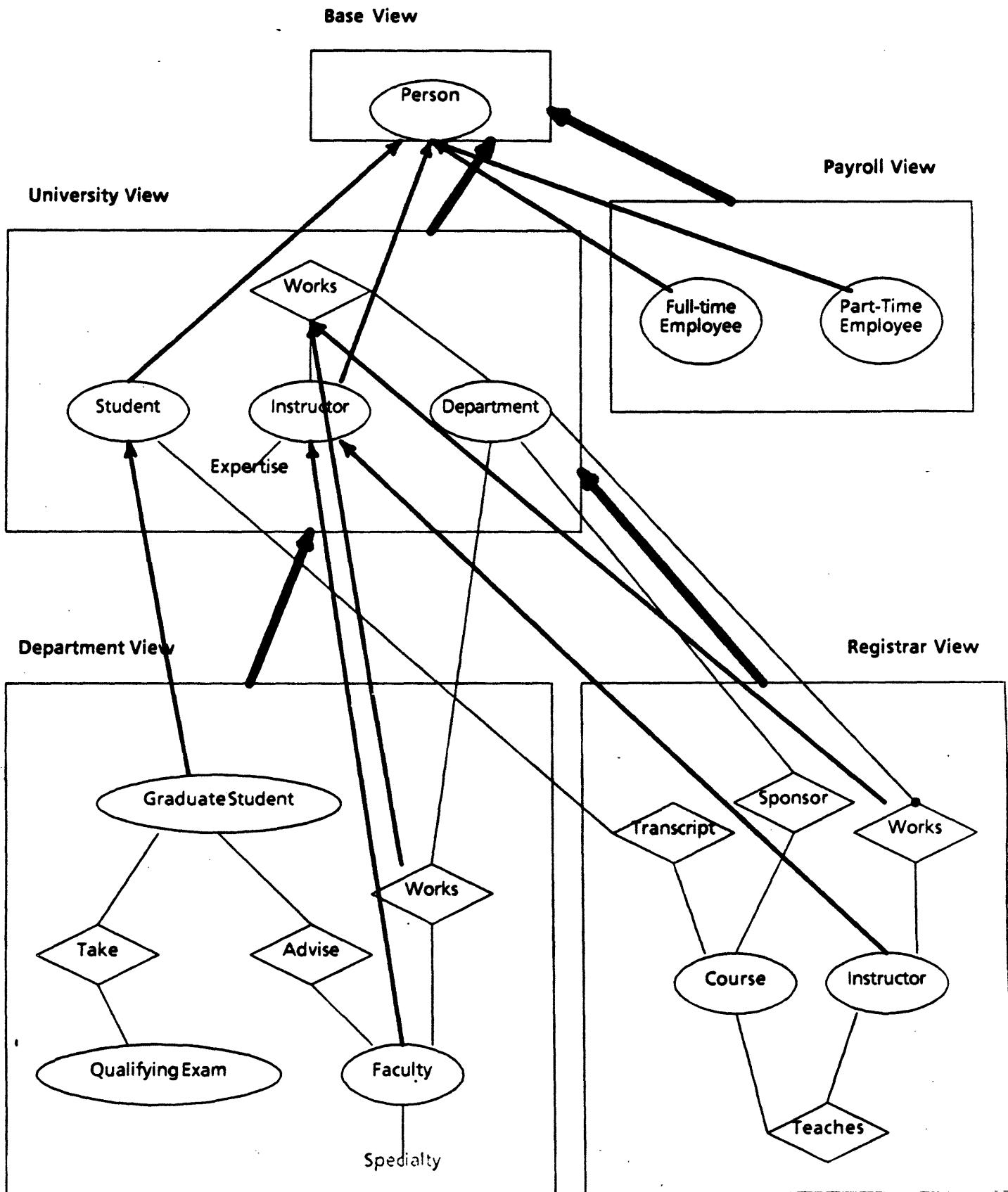
A commonly proposed solution for this problem is to provide a single "global schema" that integrates all of the different objects from each local database into one global structure. Doing this integration often involves creating virtual data types, of which the local types are special cases. In our framework, this approach is equivalent to the External Common Language scheme because each local system can continue using its own record formats and can use the global schema to translate into and out of the format used by other systems. As such, it has the problem associated with the External Common Language scheme -- namely, that some meaning would be lost in translation. A query, if expressed locally, has to be translated into a global language, and then to the languages local to the databases where the actual data are stored. Furthermore, when the number of local databases is large or when local databases change frequently, maintaining a single global schema may become unwieldy [Lee 88].

A modular organization like PSV can help solve some of these problems of the global schema approach. PSV supports incremental sharing by allowing users to establish shared schemas and translation rules as needed. These translation rules can be used not only to translate data records from one view to others, but also to translate the queries themselves. Also, when new databases are created as specializations of existing views, certain translations can be performed automatically without any explicit mappings. This way, a database can automatically share data with all the databases which adopt any of its parent views. In the following, we illustrate these features by showing how the ideas from PSV could be applied to a simple example. This example is a somewhat modified version of the example used in [Elmasri et al. 86] to illustrate their global schema approach.

Figure 5.1 shows five views. Some of these views are associated with databases. There is the university database that keeps only information valuable university-wide, and departmental and registrar databases that keep local information. Given these databases, consider the following query: "Find all instructors in Computer Science who either teach CS106 or whose expertise includes 'expert systems'" Suppose the query is made to the Registrar view. First, the query is processed at the Registrar database in the usual way, i.e. the Department field of WORKS, the Course field of TEACHES, and the Expertise field of INSTRUCTOR are

Figure 5.1 Organization of Database Schemas using PSV

 Superview Relation  
 Supertype Relation  
 Relationship Link



looked up to retrieve instructors who satisfy the query. However, since the Registrar database only contains information about the instructors teaching in the current semester, querying the registrar database alone would miss instructors not teaching this semester. To find them, the query has to be run on the other databases as well.

If there are explicit mappings between views, say between Registrar View and Department View, then the query would run at the Department database as well. For example, if there is a mapping between FACULTY in Department view and INSTRUCTOR in Registrar view, FACULTY in various department databases can be looked up and also included in the answer to the query. Even in the absence of explicit translation rules, the internal common language scheme can be used to automatically translate the query to the university view. The resulting query can then run at any database that adopts the University view -- the university and the department databases.

## 6.2 Electronic Data Interchange

An increasing number of companies are now using electronic connections between independent organizations to exchange certain standard business forms (such as purchase orders and invoices) [TDCC 88]. This kind of exchange (called Electronic Data Interchange or EDI) is greatly facilitated by common formatting standards for the forms, and many industries have begun to develop such standards. For example, there are now ANSI standards for generic forms such as Purchase Orders, Purchase Order Change Requests, and Invoices, and industry specific forms such as Shipment Information fo Air Carriers, for Motor Carriers, and for Ocean Carriers.

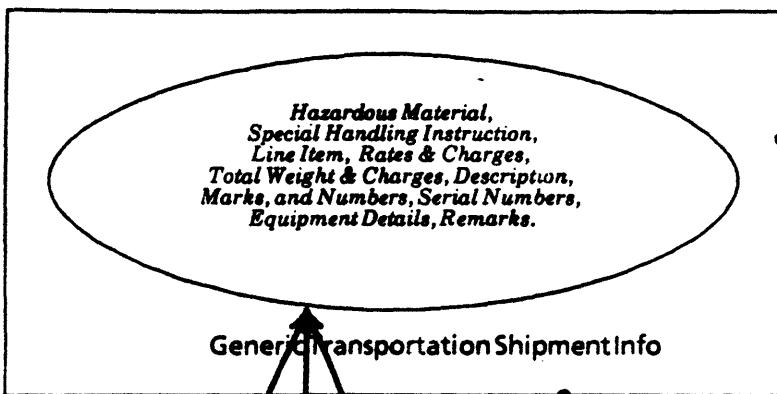
As currently used, these different types of forms constitute an essentially "flat" space, with no notion of specialization or inheritance, but it appears that the ideas about type inheritance and incremental sharing we discussed above could be of use in EDI systems. For example, if EDI forms are defined hierarchically, then it would be easier to add new types of forms that shared many of the characteristics of previous forms. Shipment information forms for a new transportation medium (like bicycle couriers, for instance) could be added by specializing a generic Shipment Information form already present. More interestingly, certain automatic translations between forms

**Figure 5.2 Organization of EDI Transaction Sets using PSV**

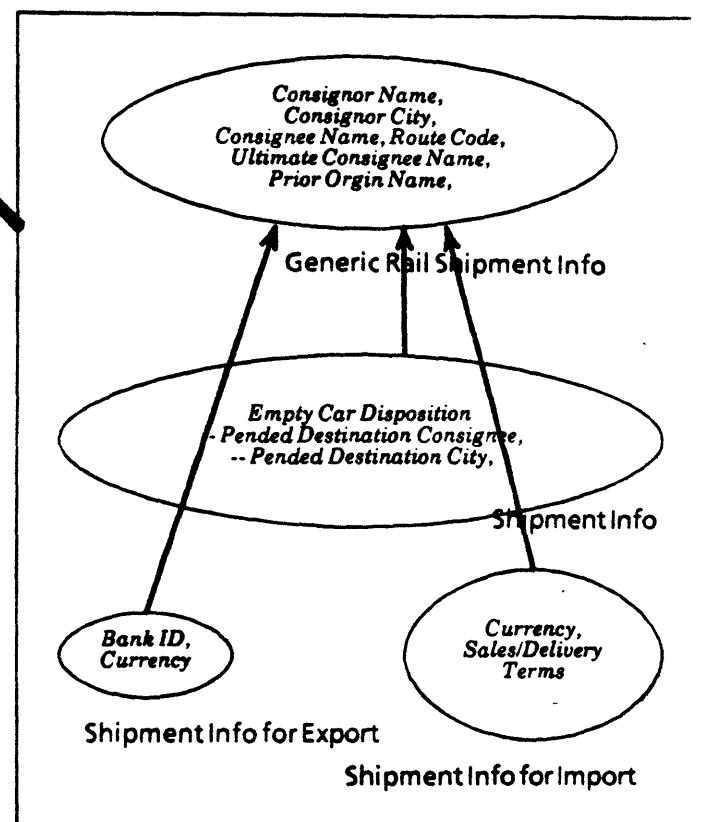
Views are represented by the squares, types by the ovals, and fields for a given type by the italicized text items in an oval.

- Superview Relation
- Supertype Relation

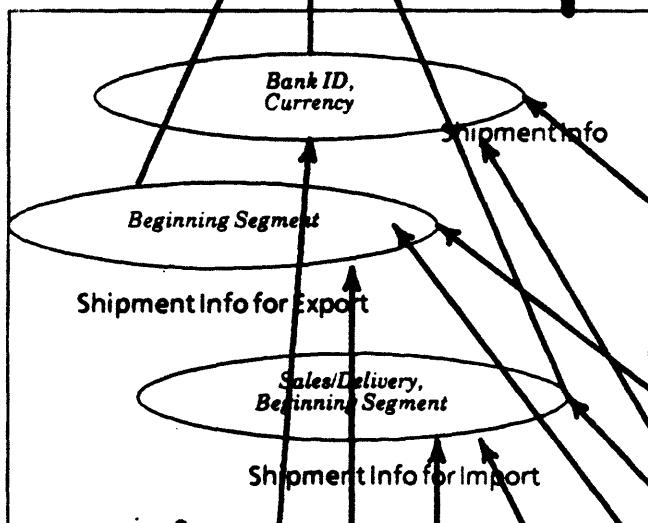
## Generic Transportation View



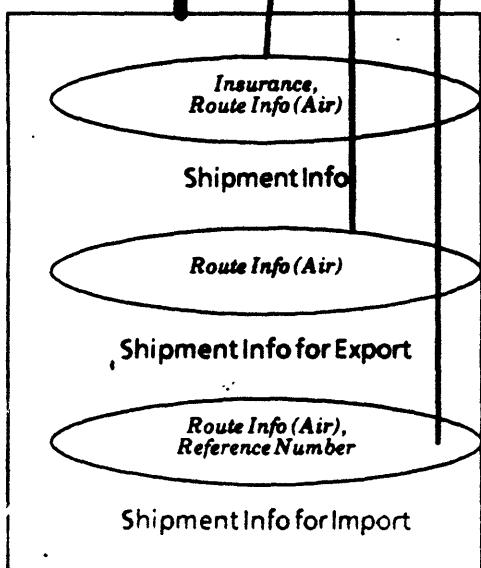
## Rail View



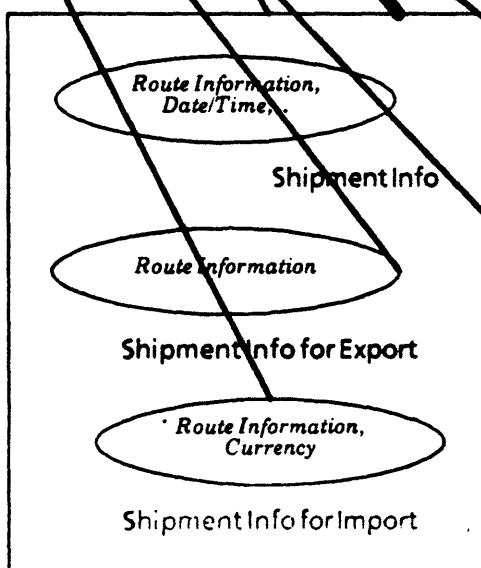
### Generic Air/Motor/Ocean View



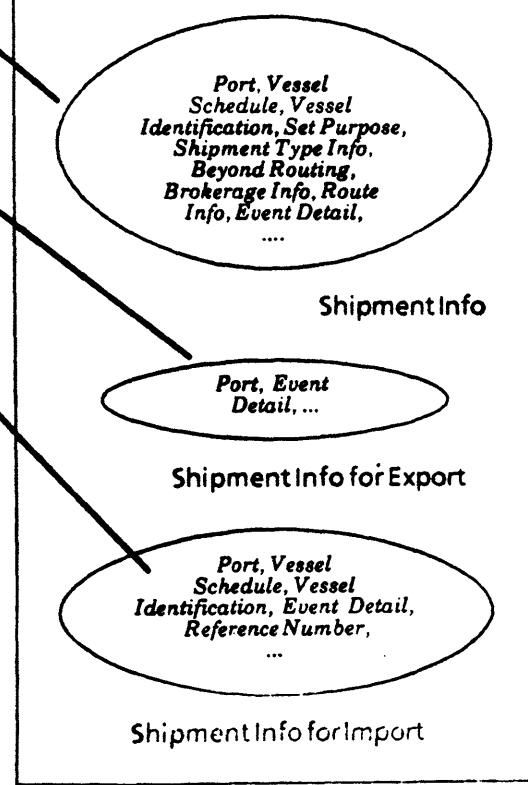
## Air View



MotorView



## Ocean View



would be possible without anyone needing to explicitly define them. For instance, if a change of plans required an air shipment to be re-routed by truck, most of the fields for the new shipment information forms could be filled in automatically from the old ones. In some cases, this might be all that is needed. If not, explicit translation rules could be created or, in special cases, people could complete the translation manually.

To illustrate more concretely how these ideas might be implemented, Figure 5.2 shows a possible organization of the EDI forms (called "Transaction Sets") for various kinds of shipment information. The "leaves" of this hierarchical organization contain all the data elements in the currently defined standards for the different types of shipment information forms [TDCC 88]. The figure also shows how some new generic forms can be defined at various levels of abstraction to take advantage of the type inheritance mechanism we have proposed here.

## 7. Conclusion

In this paper, we have considered a fundamental problem of coordination: How can groups that use different languages communicate with each other? This problem arises repeatedly in human organizations and also, increasingly, in distributed computational systems. We have characterized and evaluated a set of generic solutions to this general problem and illustrated their application in several practical contexts: the Object Lens cooperative work system, the integration of heterogeneous databases, and the use of Electronic Data Interchange standards. In particular, we described a composite scheme called Partially Shared Views that combines many of the best features of all the schemes we analyzed. A key insight of our analysis is that when groups communicate using objects that are arranged in a specialization hierarchy, they can take advantage of a powerful form of automatic translation: "foreign" object types can be automatically translated into their nearest common "ancestor" types and thus still retain much of their original "meaning." The partial interoperability attained automatically in this way makes possible a much more flexible kind of standard. No longer does everyone have to agree about all aspects of a standard; they can still get substantial benefits from whatever agreements they do have.

We believe these ideas can help solve some of the increasingly critical problems of developing standards for interoperability in distributed computational networks. At an even more fundamental level, they may eventually help us understand coordination problems that arise in other contexts such as human organizations and neural architectures.

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